DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Feasibility of a Nationwide Program for the Identification and Delineation of Hazards from Mud Flows and Other Landslides

Chapter D. The Economics of Landslide Mitigation Strategies in Cincinnati, Ohio: a Methodology for Benefit-Cost Analysis

by

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THE ECONOMICS OF LANDSLIDE MITIGATION STRATEGIES IN CINCINNATI, OHIO: A METHODOLOGY FOR BENEFIT-COST ANALYSIS

Introduction

To protect individuals against injury or catastrophic loss from a natural hazard, public safety rules and regulations can be imposed that require individuals to undertake mitigation activities. The strategy for mitigation adopted by a community will be influenced by knowledge of the hazard-producing processes and where they occur within the community. A successful mitigation strategy employs decision rules, regulations, and specifications in a way that yields positive net benefits to the community; that is, so that the benefits of implementing specified mitigation activities exceed the costs of performing those activities. The optimum strategy would employ those procedures and regulations that yield the highest positive net benefits to the community, and generally would include a decision process regarding the identification of areas where specified mitigation activities must be implemented. The optimum plan for the prevention of losses due to a geologic hazard is a logical choice for a community mitigation strategy.

A successful community mitigation strategy should also include a means to optimize the amount and type of information collected in support of the decision process. For example, regional geologic and topographic information can be used to discriminate among areas having different potentials for landslide hazard. With information about the relative hazard potential among locations within the area of the community, estimates of the relative net benefits (utility) of alternative mitigation plans can be made and the optimum mitigation strategy can be identified. A community can then develop a decision process that requires incurring the expense of site investigations only where the expectation of loss warrants mitigation, while choosing to avoid the added costs of construction for mitigation in areas where the expected losses are less than those costs.

Landslide mitigation through the imposition of strict grading codes and land-use rules has been successful in reducing damages at building sites in some communities. For example, in the Los Angeles region , hillside grading codes, first imposed in 1952 and revised in 1963, have drastically reduced losses of life and property (Slosson and Krohn, 1979). Although these codes were demonstrably successful in reducing disaster losses in hillside areas, the procedure, in effect, treats all hillside sites as having approximately equal landslide hazard potential until detailed site examinations (including gathering additional geologic and soil engineering data) establish whether or not a landslide has occurred, or is likely. Based on those findings, specific design and construction procedures are then required to provide for slope stability. This procedure does not provide the community with a means to evaluate the cost-effectiveness of gathering additional information on a community-wide (or regional) basis, nor to design an optimum strategy for mitigation. Its application, in areas where landslide hazards are less well known than in southern California, is hindered by concern that imposing the added costs of landslide mitigation may not be warranted by the expected losses to be avoided in a specific community. The results of the present study indicate that regional geologic information can be used to improve the reliability of predicting the distribution of landslide probability, thereby improving community capability to measure the economic value of implementing specific mitigation requirements in specific areas. The expected benefits of acquiring additional site information needed to design effective mitigation activities at specific sites can then be estimated from the regional data. Although the present study concentrates on landslide hazards, the technique can be applied to other geologic hazards as well.

Landslides are a persistent problem in every section of the United States. Of the 50 States, 40 are prone to significant property losses from landslides every year. Many large urban populations occupy areas susceptible to landsliding. As examples, estimates of historic private and public loss average about $6,000,000 annually in the San Francisco Bay region, $4,000,000 in Allegheny County, Pennsylvania, and $5,000,000 in Hamilton County, Ohio (Fleming and Taylor, 1980). Community efforts to reduce the rate of expected future losses could be designed to maximize expected net benefits only if the relative hazard potential among different areas of the community can be identified. To develop a methodology for estimating net benefits of alternative strategies empirically, we chose part of Cincinnati, Ohio, as a case study (fig. D-1).

Figure D-1. Near here

This study could not have been accomplished without the willing cooperation and assistance of many people other than the authors. For the City of Cincinnati, Ram Jindal, James Johns, Don Rosemeyer, and Bill Spurling provided data on landslide occurrence and damage estimates, and Robert Duffy assisted in acquiring estimates of costs for grading activities. For Hamilton County, Ronald Miller and Roger Pfeil provided data on landslide occurrence and damage estimates. Paul Beauchemin (USGS) assisted in the acquisition of damage data and in identifying map locations of street addresses where damage had been recorded. Steve Obermeier (USGS) assisted in the identification of the costs of engineering solutions to slope-stability problems. Steve Pousardien (USGS) assisted with manual determinations of maximum slope used in initial phases of the work. Vincent Caruso and Robert Claire (USGS) acquired digital elevation data for the study area, and wrote and operated the programs that determined maximum and average slope from the digital data. Leonard Gordon, Susan Fleisig, William Watson, and Thomas Kugel, all of the Geological Survey contributed valuable discussions of alternative approaches to the statistics and economics.

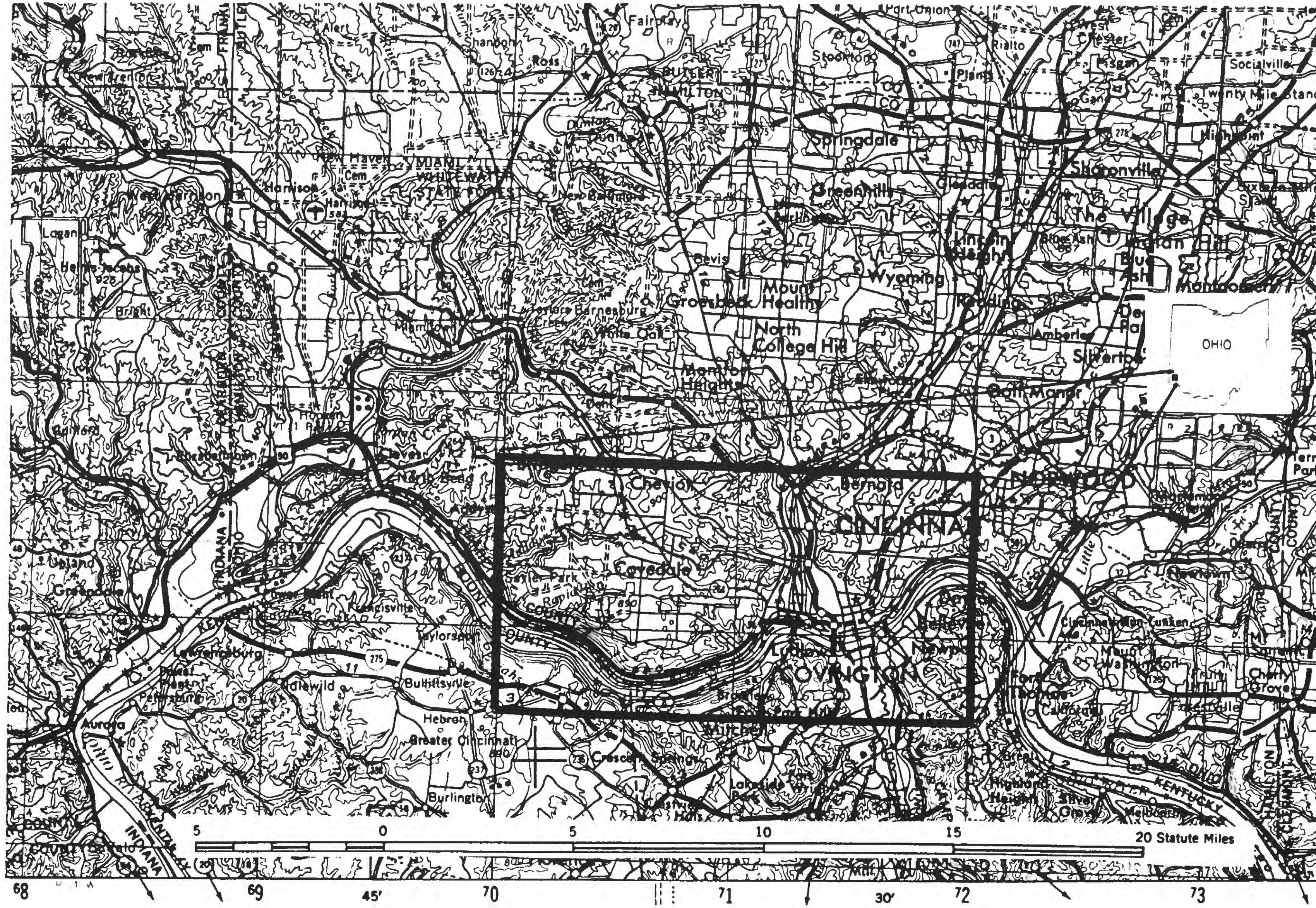

Figure D-1. INDEX MAP SHOWING CINCINNATI, OHIO, STUDY AREA

Economic Framework

The benefits of imposing a mitigation rule are received by individuals who avoid the damages that can stem from landslides. The success of an individual in avoiding losses from landslide damage depends on the way he uses available information about the potential for hazard. If the likelihood that a landslide will occur can be estimated and the cost of mitigation to prevent landslide losses is known, the individual can evaluate his level of landslide risk.

By adapting a utility model developed by Brookshire and others (1983) to evaluate the benefits of increased safety derived from building codes for earthquake-resistant construction, it is possible to estimate the value of reducing the risk of landslides. The utility model, as modified for landslides, focuses on determining an individual's willingness to pay to increase safety and to avoid property losses. The landslide utility model includes a spatial component specific to landslide-hazard occurrence. Unlike earthquake shaking, which affects very large areas simultaneously, landslides have an uneven impact in space and time, commonly distributed among relatively small parcels of land. Thus, when valuing the utility of an individuals' safety and property relative to a landslide hazard, he needs to consider the likelihood of a landslide occurring at a specific location.

In a systematic approach to assessing levels of landslide risk, an individual attempts to maximize the sum of expected utility under the conditions imposed by a two-state world: 1) if no landslide occurs (probability = 1-P), and 2) if a landslide does occur (probability = P). This can be expressed by the equation:

$$E(U)=(1-P)(1-\Pi^{o})U(W) + P(1-\Pi^{o}-R)U(W-L) \qquad \text{(D-1)}$$

Where:

- $E(U)$ = expected utility;
- P = annual probability of a landslide;
- Π^{o} = initial risk of death for an individual;
- R = additional risk of death if a landslide occurs;
- W = individual's wealth;
- $U(W)$ = utility function of individual's wealth (strictly concave);
- L = property losses to the individual's wealth if a landslide occurs;
- $U(W-L)$ = utility function of individual's wealth as reduced by landslide losses.

In the state of the world where an event does occur, risk of death is increased by R and wealth is decreased by L, as represented in equation D-1 by the term $P(1-\Pi^{o}-R)U(W-L)$. If mitigation is undertaken, it presumably will reduce risk of both landslide-related death and property loss, and it is plausible to assume that R and L will decrease with increasing stringency of landslide mitigation measures (C). If P, Π^{o}, and E(U) are fixed, a compensating variation measure (Varian, 1984, p. 264) of the willingness to pay for mitigation is obtained by totally differentiating equation D-1 and solving for dW/dC where it is assumed that R = R(C) and L = L(C). This yields:

$$\frac{dW}{dC} = P\Bigg(\underbrace{\frac{U}{P(1-II^{O}-R)U' + (1-P)(1-II^{O})\text{Ʉ}'}\left(\frac{-dR}{dC}\right)}_{(A)} + \underbrace{\frac{(1-II^{O}-R)\ U'}{P(1-II^{O}-R)U' + (1-P)(1-II^{O})\text{Ʉ}'}\left(\frac{-dL}{dC}\right)}_{(B)}\Bigg) \qquad \text{(D-2)}$$

Where the prime denotes differentiation, and:

- C = index of the stringency of landslide mitigation;
- U = U(W-L), utility function in world where landslide event occurs;
- U' = U'(W-L), the incremental change in utility if a landslide occurs;
- Ʉ = U(W), utility function in world where no event occurs;
- Ʉ' = U'(W), the incremental change in utility where no landslide occurs.

An approximation of the expected benefits of increased safety to the individual (decreased risk of death) is yielded by term (A) in equation D-2. Term (B) in equation D-2 is an approximation of the expected benefits of property losses avoided from imposing a mitigation strategy. Term (B) in (D-2) becomes simply (-dL/dC) when the remainder of the term is approximately equal to unity, with the consequence that

$$\frac{(1-II^{O})\text{Ʉ}'}{(1-II^{O}-R)U'} = 1 \qquad \text{(D-3)}$$

since U' = U'(W-L) and Ʉ' = U'(W), and if L = 0, then Ʉ' = U'; and if R also = 0. However, as L becomes positive and nonzero, U' becomes greater than Ʉ'; and if R becomes positive and nonzero, $(1-II^{O})$ becomes greater than $(1-II^{O}-R)$. The effects of increasing R and L in equation D-3 are in offsetting directions. Consequently, if R and L are small or offset each other by the same magnitude, equation D-3 should remain close to unity, and the term (B) in equation D-2 is approximately equal to (-dL/dC), permitting the reduction in property losses attributable to mitigation to be defined as P(-dL/dC).

Hazards Information and Probability: An Illustrative Case Study

A technique to estimate probabilities of landslides for specified areas in Cincinnati, Ohio, has been developed for this study. Probabilities are estimated for square areas (grid cells) at two different grid sizes in order to identify what scale of detail best describes the state of nature in different areas of the city. The computed spatial probability can be combined with 1980 property values to estimate the expected damage avoided or net benefits of a given level of mitigation.

A probability model for landslide occurrence was derived from the mechanical process that governs landslides, the existing physical state of a hillside, and with construction activities providing exogenous triggering factors. In the greater Cincinnati, Ohio, area (including other Hamilton County locations), landslides are a persistent cause of property damage of more than $5,000,000 annually. To structure the compilation of earth-science and other data into a probability model for predicting the likelihood of a landslide, a part of the Cincinnati metropolitan area was selected for study and divided into cells comprising grids of 100-m and 500-m squares. At the smaller grid size, the study area is divided into 14,255 cells, 450 of which had at least one landslide in the 10-year period 1970-1979. For matrices of both cell sizes, a logit transformation (Theil, 1971, p. 632) was utilized to estimate the probability of a landslide occurring in a given cell as a function of regional physical information about the cell.

For the purposes of the study, we have adopted the following set of simplifying assumptions:

1. There are two states of the world

   a. A landslide does occur in a cell.
   b. A landslide does not occur in a cell.

2. The probability of a landslide within each grid cell is constant over time. The 10-year sample of landslide occurrences in Cincinnati is representative of a longer term.

3. Implementing a mitigation activity requires an initial investment cost, but no operating costs.

4. The costs considered are those related to an engineering solution (grading) for landslide-hazard mitigation: non-structural mitigation strategies, such as zoning restrictions, are not considered.

5. Mitigation is assumed to be 100 percent effective, i.e., if a mitigation activity is implemented in a cell, landslide loss will not occur in that cell.

6. Residential buildings, once damaged, become a total loss; and, if a landslide occurs in a grid cell, then all residential buildings in that cell will be totally destroyed.

7. The 1980 distribution, density, and types of buildings in the study area reflect no prior knowledge of landslide probabilities, nor imposition of mitigation rules, in the cells where they are located. This assumption permits estimating the benefits of mitigation by a theoretical "rebuilding" of Cincinnati as it is today, and comparing expected losses with and without the imposition of mitigation rules.

8. The costs of mitigation in a cell are those engineering and construction costs attributable to grading activities that follow the slope-stabilization procedures in Chapter 70 of the Uniform Building Code (1979), a model code published by the International Conference of Building Officials, and vary with the steepness of the hillslope in the cell. The total costs for the study area vary with the number of cells in which

mitigation is required by various rules that could be imposed by the community.

9. Modification of existing structures in a cell to conform to mitigation rules (retrofitting) is not considered in the analysis of costs of mitigation. (Modifying existing foundations and structures to fit more-stringent code provisions is generally much more costly than initial engineering and construction to the same code standards.)

The natural geologic setting of the Cincinnati area includes earth materials of different strengths that locally interact with seasonal rises in ground water and with certain kinds of construction activity to trigger landslides. The landslide processes most common in the Cincinnati area are slab-shaped failures of unconsolidated earth materials (colluvium, glacial till, and lake clays) that commonly fail on inclined surfaces approximately parallel to the ground surface.

The probability (P_i) that a landslide will occur in a particular grid cell is a function of 1) initial state-of-nature factors that are relatively constant until altered by 2) triggering factors that vary with time, and 3) process factors dependent on the general mechanism of failure. In developing a statistical probability model, these factors provide the independent variables for which a relationship must be determined for a dependent variable describing whether a landslide has occurred in the cell. Because the probability model must accommodate a dependent variable that is binary, - either P=1 (yes, a landslide has occurred) or P=0 (no, a landslide has not occurred) - and the standard linear probability model derived from ordinary least squares regression could yield values outside the range of 0 - 1, a logit transformation - $\ln(P/(1-P))$ - was used so that the estimated probabilities remain between 0 and 1.

Data for the Cincinnati study area were collected and compiled in digital format. Initial state-of-nature factors included topographic and geologic regional data. Maximum and average slope were calculated for each cell from filtered digital elevation data. The programs for filtering the digital elevation data, and for calculating maximum and average slope, were developed and executed for this study by Robert Claire and Vincent Caruso of the Geological Survey. Shear strengths of dominant surficial materials, from tests made on materials from various Cincinnati sites, were extrapolated throughout the study area on the basis of a reconnaissance surficial geologic map, compiled on a 1:24,000 scale base. This extrapolation permitted assigning a single shear strength to each cell.

From the results of previous studies of landslide processes in Cincinnati by Fleming and others (1981), the principal triggering factors were identified as seasonal changes in ground-water level and new construction. In the absence of detailed data on the differences in ground-water-level changes for each cell, it was assumed that seasonal changes in ground-water level are uniform for all cells in the study area. Construction data, classified according to new road construction, new house construction, and new other construction, were determined for each cell by comparing USGS 1:24,000 scale maps as photorevised in 1970, with aerial photographs taken in 1980 for further photorevision. For each cell and each class of construction, it was determined whether construction had occurred, or had not occurred, and digitally represented by a 1 or 0, respectively. In addition, the influence of construction in proximity to cells with steeper slopes above was accommodated by assigning a yes (1) or no (0) to the upslope cell.

Because most of the landslides in the study area have the general shape of thin planar slabs, and failed on slip surfaces approximately parallel to the topographic slope, the failure process was represented by a single factor, the simple sliding block frictional relationship of:

$$D = \frac{\tan \phi'_r}{\tan B}$$

where:

$\tan \phi'_r$ = average residual shear strength (effective stress basis) of the geologic material in the cell, and

$\tan B$ = tangent of the angle of the average topographic slope in the cell.

The ratio (D) represents the failure process in terms of the average physical properties of the cell. Among cells with the same average properties, as represented by (D), those with the steepest maximum slopes are the most susceptible to failure; therefore, the key state-of-nature variables for landslide probability in the Cincinnati area are (D) and maximum slope (MS). Data on past damaging landslide occurrences were provided by the City of Cincinnati and Hamilton County for the 10-year period 1970-1979. The variables are summarized in Table D-1. The distributions of the dependent

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Table D-1. Near Here

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variable (known landslide damage), the independent variables, and other related factors are shown by Figures D-2 to D-7.

Figures D-2 through D-7. Near here

Using the notations listed in Table D-1, the relation between independent and dependent variables takes the form:

$$SLD = f(D, MST, NR)$$

The use of the non-linear logistic multiple regression model (the LOGIST procedure of Harrell, 1983) requires the use of maximum likelihood estimate (MLE) procedures, rather than ordinary least square methods for regression. The MLE technique yields an intercept and a coefficient for each applicable independent variable, and appropriate test statistics for significance of the variables and goodness of fit for the model. (The independent variables AST and SS are combined in the variable D, and the test statistics for NH and UP

Table D-1. Variables Used in the Study

DEPENDENT VARIABLE:

Landslide = SLD = 1 if one or more landslides occurred in a cell between 1970 and 1979; 0 otherwise.

INDEPENDENT VARIABLES:

Hillside Stability Index: (A measure of mechanical stability for slope materials in a cell.)

$$D = \frac{\tan \phi'_r}{\tan B} = \frac{\text{Tan (angle of internal friction)}}{\text{Tan (average hillslope angle)}}$$

Existing Physical State of a Cell:

MST = Tangent of maximum natural slope in a cell, calculated from digital elevation model.

AST = Tangent of average natural slope in a cell (tan B), calculated from digital elevation model.

SS = Soil shear strength, i.e., the ability of a soil material to resist deformation and hence movement; soil mechanics laboratory reports of residual shear strength ($\tan \phi'_r$) for representative samples, extrapolated on the basis of the geologic map.

Triggering Factors:

NH = 1 if one or more new homes were constructed in the cell area during the period of 1970 to 1979; 0 otherwise.

NR = 1 if one or more new roads were constructed in the cell area during the period of 1970 to 1979; 0 otherwise.

UP = A physical variable representing whether or not construction activity occurred directly downslope from a particular cell. If construction did occur downslope, and the average slope between the two adjacent cells is greater than or equal to 10°, a value of 1 is assigned; 0 otherwise.

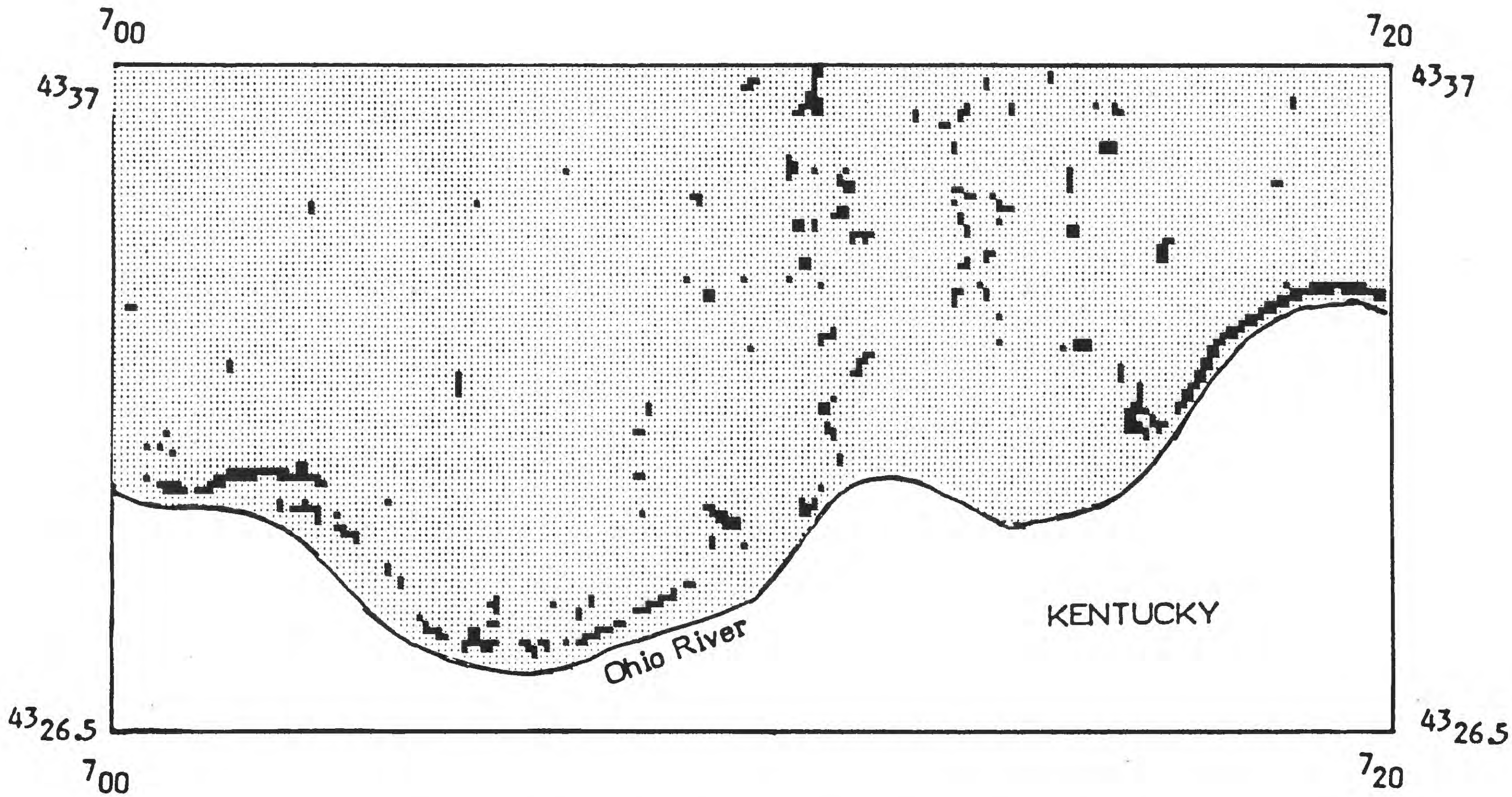

Figure D-2. CELLS WITH LANDSLIDE DAMAGE, 1970-1979 (Shown in black)
(100-meter cells; UTM coordinates)

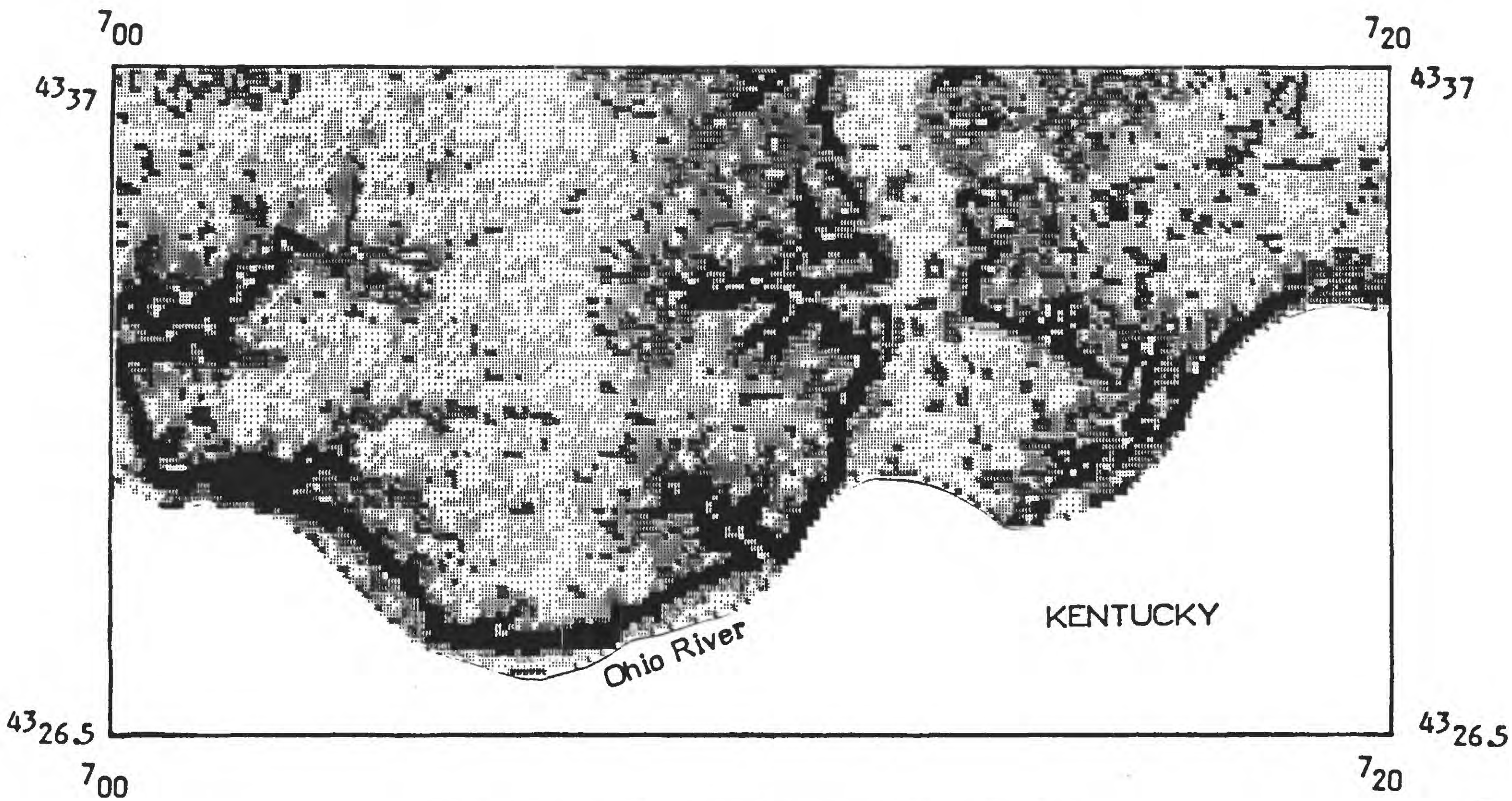

Figure D-3. MAXIMUM SLOPE IN EACH CELL
Derived from Digital Elevation Models
(100-meter cells; UTM coordinates)

Explanation
(Showing range of slope in degrees.)

greater than 14°

$9 - 14^{\circ}$

$5 - 8^{\circ}$

$0 - 4^{\circ}$

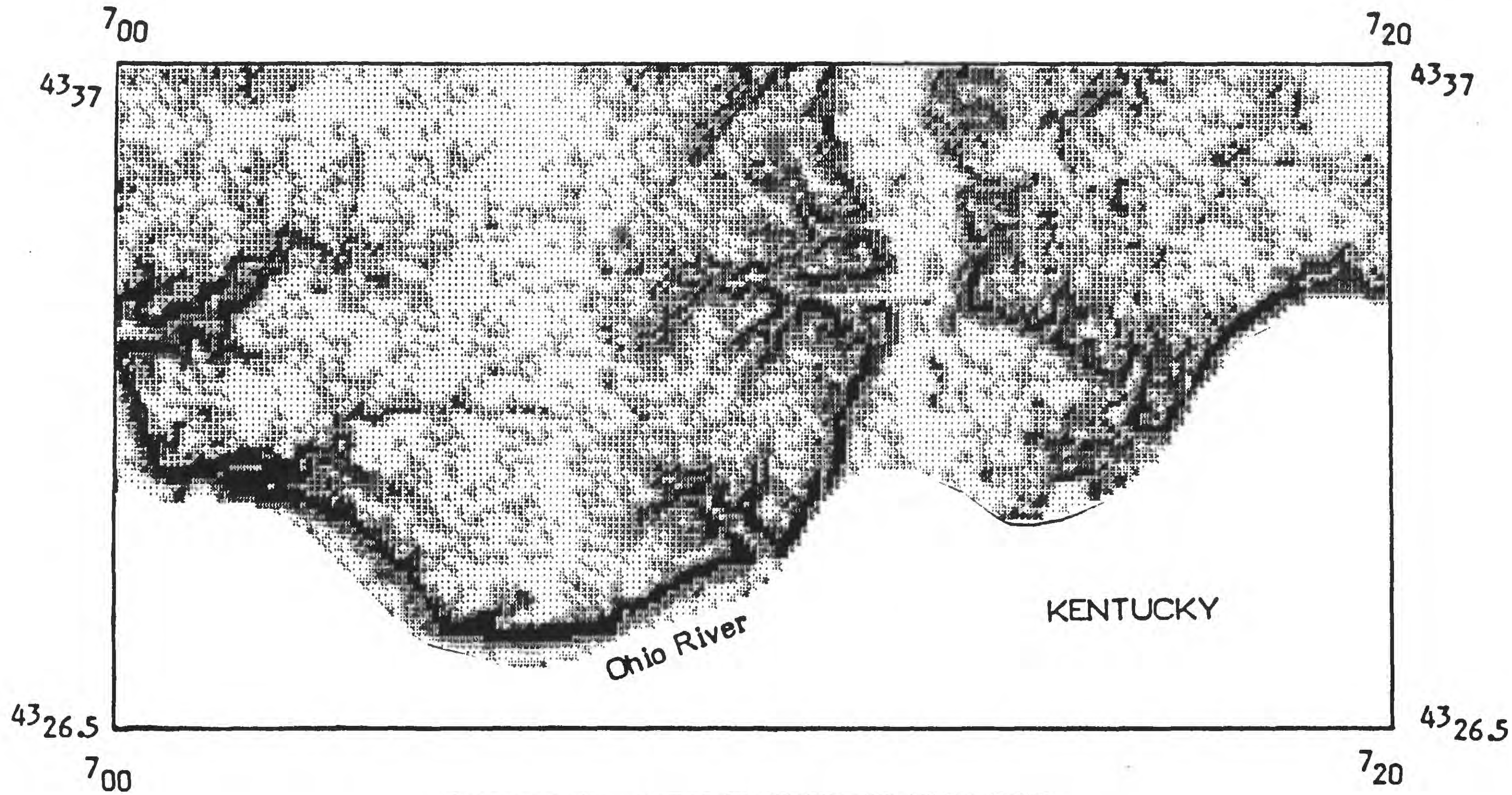

Figure D-4. AVERAGE SLOPE IN EACH CELL
Derived from Digital Elevation Models
(100-meter cells; UTM coordinates)

Explanation

(Showing range of slope in degrees.)

- greater than 14°
- 9 - 14°
- 5 - 8°
- 0 - 4°

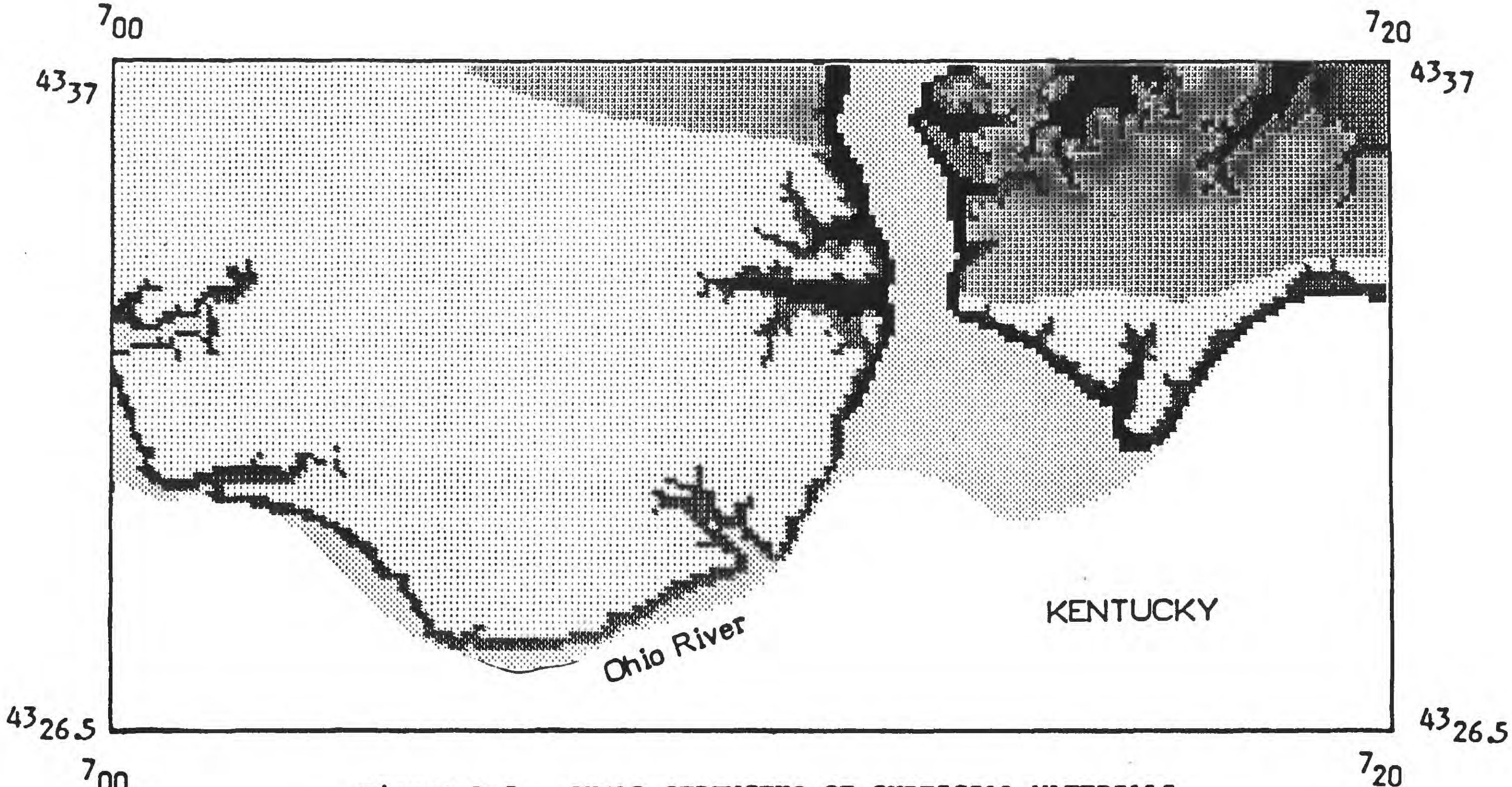

Figure D-5. SHEAR STRENGTHS OF SURFICIAL MATERIALS
(100-meter cells; UTM coordinates)

Explanation

Tan $\emptyset'_r$, extrapolated on the basis of reconnaissance geologic map.

0.25	Glacial lake clays
0.34	Colluvium
0.49	Till
0.65	Alluvium
0.78	Fairview Fm.

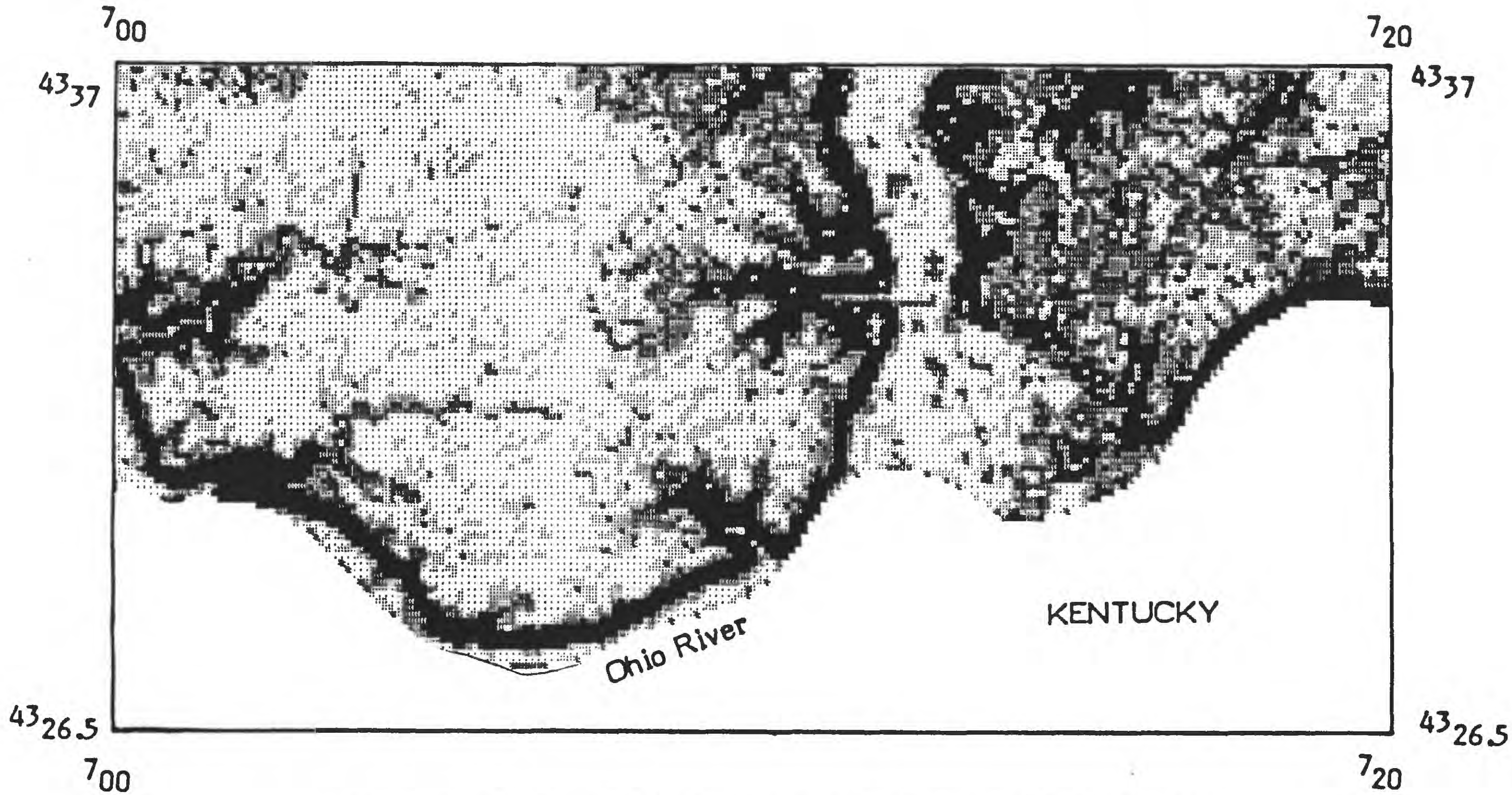

Figure D-6. D - RATIO -- Tan $\emptyset'_r$/Tan (average slope)
(100-meter cells; UTM coordinates)

Explanation

0 - 3

4 - 6

7 - 9

greater than 9

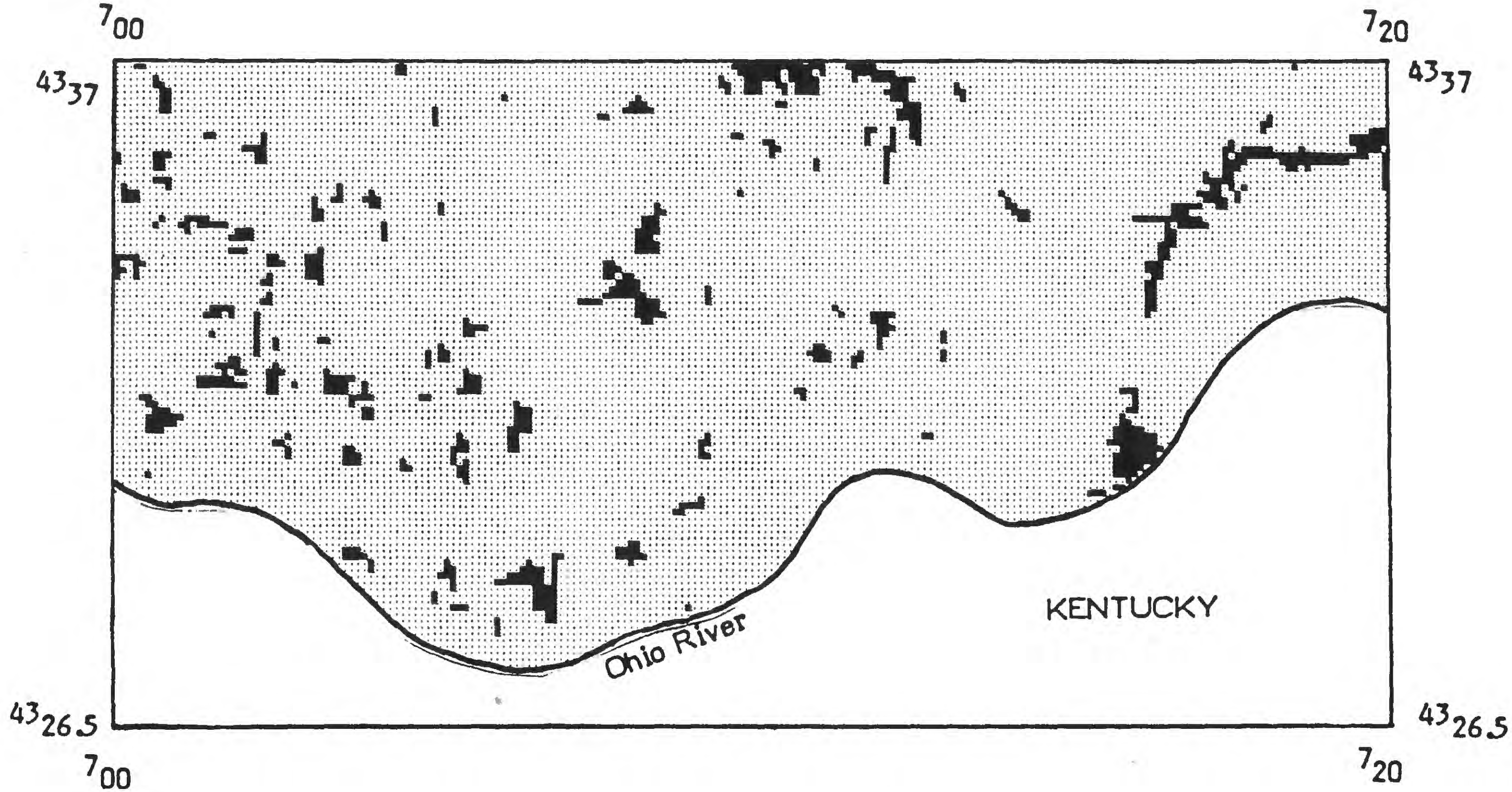

Figure D-7. CELLS WITH NEW ROAD CONSTRUCTION, 1970-79 (Shown in black)
(100-meter cells; UTM coordinates)

indicate they are not significant.) The logit transform, $\ln(P_i/(1-P_i)) = a + b(D_i) + c(MS_i) + d(NR_i)$ can then be solved for P_i, yielding a discrete predicted probability for each cell.

Separate regressions were performed for two sets of independent variables for each of two different grid sizes so that different models could be compared to determine whether those specified solely by slope and triggering factors would be improved by the addition of shear-strength and failure-mechanism factors. By comparing the different models listed in Table D-2, an equation can be chosen that best represents the probability of a landslide occurrence.

Table D-2. Near Here

The test statistics listed in Table D-2 show that hillside stability index (D), maximum slope, and new road construction variables are all significant in the equation for 100-meter cells, while the hillside stability index and the maximum slope are significant in the equation for 500-meter cells. All four equations are significant at the 99-percent level. The signs of all variables are as hypothesized. For example, as D increases, the probability of a landslide diminishes. The new house (NH) and construction downslope (UP) trigger variables, though, are not statistically significant.

The last four columns in Table D-2 represent goodness-of-fit measures associated with qualitative choice models. Following Maddala (1983), the R^2 and the upper bound of the empirical R^2 are computed. In addition, the indirect pseudo-R^2 is calculated from the likelihood-ratio test by two different methods. For both cell sizes, geologic information significantly contributes to the model as measured by chi-square statistics. The variable (D) is significant at the one-percent level for both the 100-meter and 500-meter cell sizes.

The use of both 100-meter and 500-meter grid sizes approximates the difference in utilizing regional topographic and geologic map data collected and compiled at scales of 1:24,000 to 1:100,000, and the use of more generalized maps at 1:250,000-scale and smaller. (Although these statistical procedures might be used with regional map data to evaluate cells smaller than 100 x 100 meters, smaller cells approach single lots in size and are more suitable to site-by-site geotechnical evaluations of stability.) For both grid sizes, there is a significant improvement in model chi-square with the addition of geologic information. Both the D variable and the maximum slope are significant at the 99-percent level for the 100-meter grid model. The equations with geologic information have relatively better fits than those without the additional information at both grid sizes. For these reasons, we have chosen to use the "slope and geology" probability equations over "slope only" probability equations to determine the expected value of the property at risk in a cell.

Although the probability equations at both cell sizes perform well statistically, the 100-meter equation identifies tracts of land that more

Table D-2. - Regression Results -- Intercepts, Coefficients, and Test Statistics of Probability Models for Predicting Landslides in the Cincinnati, Ohio, Area

Model	Intercept	$Log_e(D)$	$Log_e(MST)$	$Log_e(AST)$	NR	Model Chi Square	Empirical R^2	Upper Bound[h] for Empirical R^2	Pseudo R^2 (Maddala)[i]	Pseudo R^2 (McFadden)[j]
500 Meter Cells (601 observations):										
SLD = f (AS)						163.26	0.24	0.65	0.37	0.26
Coefficient	5.78			3.16						
Standard error[k]	0.64			0.29						
Chi square[k]	82.80			116.16						
SLD=f (D, MS)						177.2	0.25	0.65	0.39	0.28
Coefficient	3.49	-1.79	1.31							
Standard error[k]	0.46	0.31	0.46							
Chi square[k]	65.90	32.41	8.25							
100 Meter Cells (14,255 observations):										
SLD = f (AS, NR)						803.3	0.05	0.24	0.22	0.20
Coefficient	1.29			2.31	0.79					
Standard error[k]	0.16			0.09	0.17					
Chi square[k]	62.14			639.27	20.19					
SLD= f (D, MS, NR,)						951.8	0.06	0.24	0.26	0.24
Coefficient	-0.23	-1.45	0.72		0.77					
Standard error[k]	0.19	0.11	0.18		0.18					
Chi square[k]	1.47	168.77	15.65		18.94					

h Upper bound is given by $0 \geq R^2 \leq 1-(L_w)^{2/n}$ (See Maddala, 1983).

i Pseudo $R^2 = \dfrac{1-(L_w/L_\Omega)^{2/n}}{1-(L_w/L_{max})^2}$ (See Maddala, 1983).

j Pseudo $R^2 = 1-\left(\dfrac{Log_{10}L_\Omega}{Log_{10}L_w}\right)$ (See McFadden, 1974).

} where L_w and L_Ω are determined from parameters provided by the LOGIST procedure of Harrell (1983), and $L_{max} = 1$.

k ... of the intercept and coefficients

closely approximate the size of most landslides in the Cincinnati area; therefore, discrimination among areas of this size (a 100-meter grid cell = a 10,000-m^2 area) is highly desirable (fig. D-8). Because the

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Figure D-8. Near here

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dependent variable in the probability equation is defined as the occurrence of at least one landslide in a cell, the area covered by a 500-meter cell is more likely to have had at least one landslide than the area covered by a 100-meter cell, artificially raising the probability of landslide occurrence and increasing the expected value of property at risk. As a result, the 100-meter equation is more accurate than the 500-meter equation at discriminating locations potentially at risk. For example, a 500-meter cell might have a 0.75 probability of having at least one landslide within the cell. If the risk is of only one landslide of 10,000-m^2 area, it will occupy only 1/25 of the 500-meter cell area, and the probability predicted by the equation could overstate the likelihood of a landslide loss by a factor of 25. The 100-meter equation makes it possible to discriminate among the potential risks of areas that are four percent of the area of a 500-meter cell. Consequently, we have chosen to use the probability equation for 100-meter cells, with both slope and geologic information, to calculate the net benefits of alternative mitigation rules in order to identify a final mitigation strategy for the study area.

Property values, mitigation costs, and expected net benefits

Selection of an optimal mitigation plan requires comparing the expected payoffs from alternative decision rules. Combining the landslide probability for a cell, estimated by the equation for 100-meter cells, with property value estimates for each cell, yields the expected value of property at risk. In order to avoid the losses associated with the properties at risk, mitigation measures must be taken to eliminate the destructive impact of landslides. Expected net benefits are estimated for sets of hypothetical alternative mitigation rules in order to identify an optimal strategy.

The Cincinnati, Ohio, area is subject to landslides that have a much greater potential for property loss than for loss of life. In other areas, where different types of slope failure processes predominate, safety benefits are an important part of the expected utility (term A, equation D-2) and should not be neglected. (For example, debris flows such as those that occurred in the San Francisco area in January, 1982, pose a distinct threat to the personal safety of some residents.) However, for Cincinnati, the term (-dR/dC) in equation D-2 is set equal to zero because the expectation of a risk to life is unaffected by a change in the stringency of mitigation. As a result, equation D-2 reduces to

$$\frac{dW}{dC} = P\left(\frac{-dL}{dC}\right) \qquad \text{(D-4)}$$

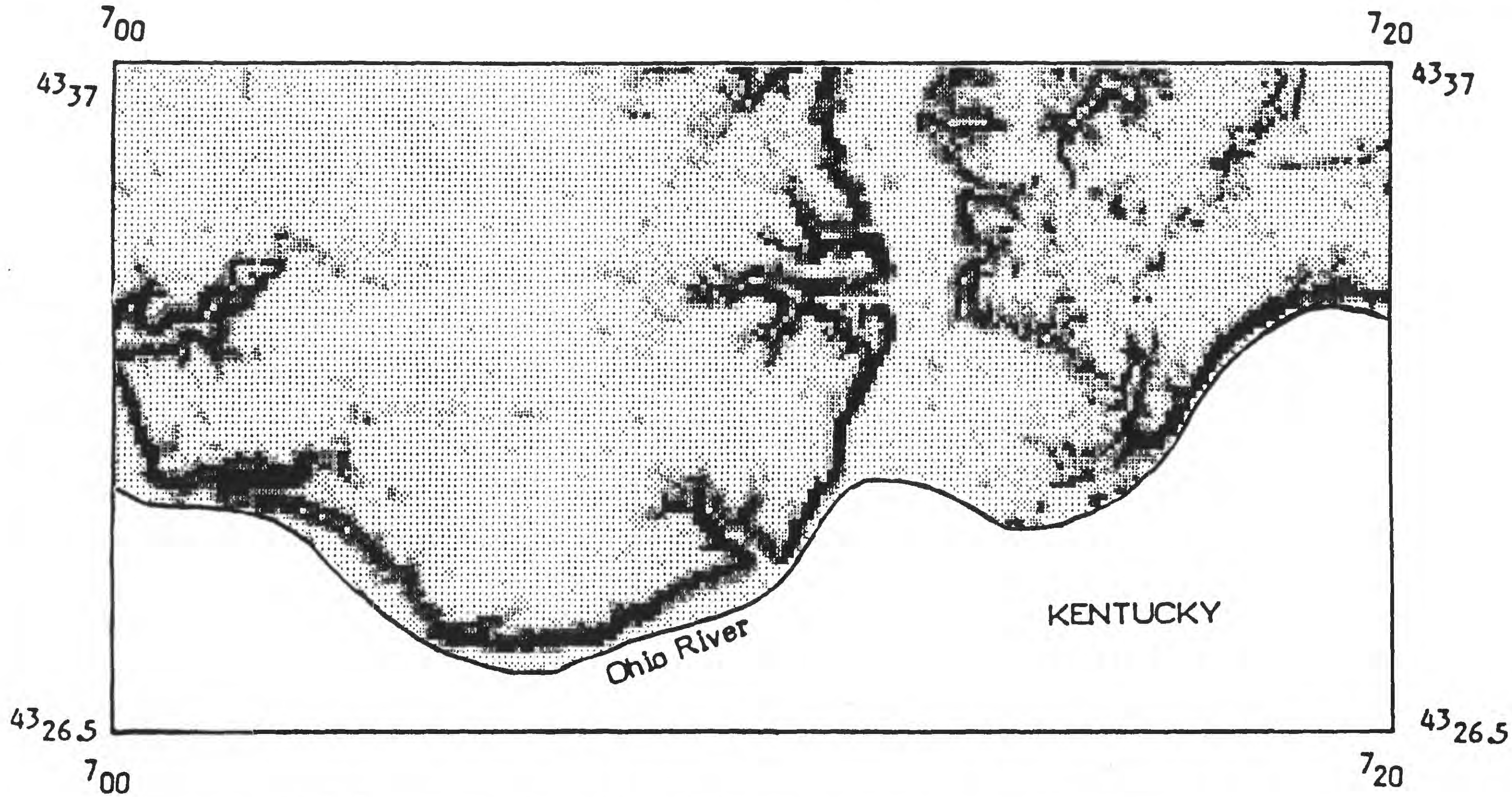

Figure D-8. ESTIMATED PROBABILITY OF AT LEAST ONE LANDSLIDE PER CELL
Cincinnati, Ohio, Study Area
(100-meter cells; UTM coordinates)

Range of estimated probabilities

0.13 and greater
0.07 - 0.12
0.04 - 0.06
0.015 - 0.03
0.000 - 0.015

which provides an approximation of the expected benefits of property losses avoided $P_i(\Delta L_i)$ from imposing migitation in the i^{th} cell, based upon equation D-4 where ΔL replaces $-dL/dC$. The expected gross benefits in the study area from implementing a specific set of mitigation rules is the sum of all the $P_i(\Delta L_i)$; therefore, the equation for the discounted expected net benefits, E(NB), of mitigating against landslide risk in Cincinnati is

$$E(NB) = \sum_i \left({}_0\int^T [P_i(\Delta L_i) e^{-rt} dt] - K_i \right) - K_m \qquad \text{(D-5)}$$

Where:

$E(NB)$ = net benefits of mitigation
T = terminal year in time period
P_i = probability of occurrance of a landslide in cell i
ΔL_i = reduction in property losses (residential structures) in cell i
e = natural logarithm base
r = discount rate
t = time in years
K_i = capital investment cost in cell i to prevent loss from landslides
K_m = cost of collecting regional scientific information.

To determine which one among j sets of mitigation rules provides the maximum annualized discounted net benefits, an optimization procedure represented by the following equation was performed:

$$\underset{j}{\text{Max}}\ E(NB) = \sum_{i \in Q_j} [(P_i \Delta L_i) - yK_i] - K_m; \qquad j = (1,\ldots,80) \qquad \text{(D-6)}$$

Where: Q_j = the set of cells, indexed by i, where $AS_i \geq AS_j$; or where $AS_i \geq AS_j$ or $SS_i \leq SS_j$
AS_j = the lowest average slope for which the j^{th} set of mitigation rules requires implementation of UBC Chapter 70 grading code provisions
SS_j = the highest shear strength of soil materials for which the j^{th} set of mitigation rules requires implementation of UBC Chapter 70 grading code provisions
y = capital recovery factor
AS_i = average slope in cell i
SS_i = shear strength of soil materials in cell i
Other variables are as in equation D-5.

The procedure described by equation D-6 can be used to identify the optimum mitigation rule using the spatial probabilities together with information on property values, cost of engineering/construction for mitigation, and cost of acquiring slope and shear strength information.

From 1980 census data, the total property value of residential housing structures in the study area is \$2.1 billion. For each cell, the property value of residential housing ($V_{i,t=1980}$) was estimated from the 1980 census data, by apportioning census block and tract values among the cells included in each block or tract (fig. D-9). If property loss would be total in the

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Figure D-9. Near here

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event of a landslide, $\Delta L_{i,t} \doteq V_{i,t}$. If mitigation is 100 percent effective in avoiding that total loss, estimation of the dollar value of the reduction in property losses, $P_i(\Delta L_i)$ follows directly once a mitigation rule is chosen and imposed by the community in those cells affected. The net benefits from a particular mitigation rule would be the difference between the expected discounted losses avoided and the cost of implementing the mitigation that prevents the loss.

Loss-prevention techniques and their associated costs include avoidance of overly hazardous areas and site preparation to maintain or enhance slope stability. These techniques are effective in preventing landslide losses in specific situations. Although detailed information for site-by-site application of mitigation techniques is unavailable for the specific area of the study, we have developed a generic engineering solution for locations in the study area, and assumed it to be 100 percent effective. The engineering solution is based upon the Uniform Building Code (UBC) cut-and-fill requirements as described in Chapter 70 (1979, p. 684-694). The cost of this approach for a specific residential structure is chiefly a function of the volume of earth that must be excavated, placed, and compacted, and increases with increasing slope (as shown in Table D-3). Where the soils are

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Table D-3. Near here

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particularly weak and plastic, as in areas of lake clay, additional costs may be incurred for special treatment, or haulage and replacement. UBC Chapter 70 calls for this decision to be made based on the professional judgement of the engineer on the particular site, a factor for which we could develop no generic engineering response or cost function.

The cost of mitigation to a community depends on the scope and comprehensiveness of requirements for mitigation activities, as determined by local authorities. They can select from among alternative kinds of regulations, including zoning ordinances, grading codes, or some combination. For instance, some areas could be zoned so that little or no construction is permitted. In other locations, residential structure density could be controlled by limiting land disturbance on any one hillside in areas of steep slopes. Alternatively, mitigation rules stipulating specific construction requirements for landslide mitigation, depending on the natural conditions of the hillside or area, would permit orderly development that could duplicate the present distribution, density, and types of buildings in the study area today. Such a hypothetical duplication permits a comparison of the benefits and costs of mitigation under different sets of rules, and where different levels of information are utilized to guide the application of mitigation rules.

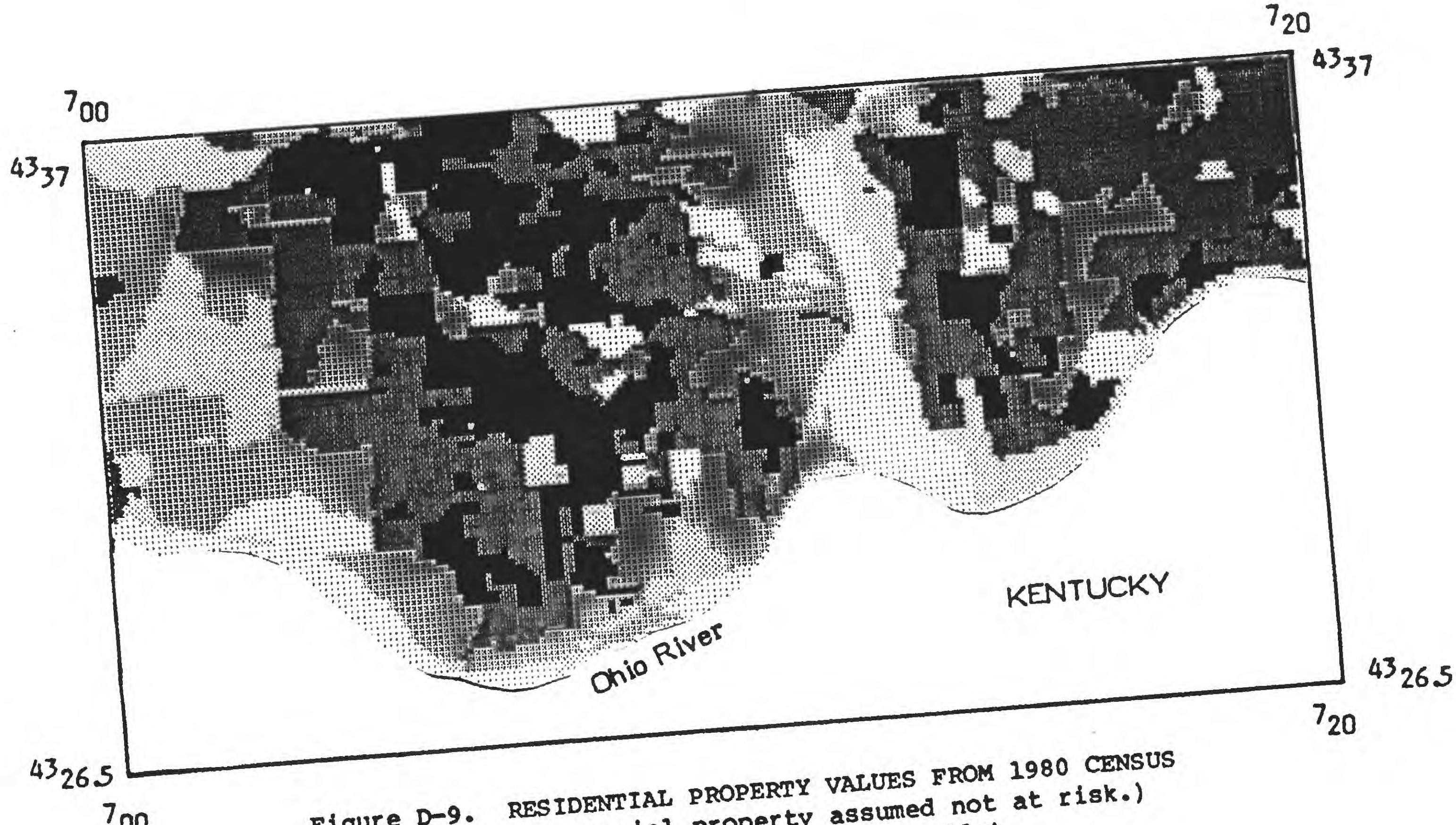

Figure D-9. RESIDENTIAL PROPERTY VALUES FROM 1980 CENSUS
(Industrial-commercial property assumed not at risk.)
(UTM coordinates, 100-meter cells)

Explanation
Range of property values in dollars per cell
(Industrial-commercial property valued at $0.)

- $250,000 - $1,000,000
- $100,000 - $250,000
- $50,000 - $100,000
- $10,000 - $50,000
- $0 - $10,000

Table D-3. Estimated Costs (per lot) for Building Site Excavation and Fill to Conform with UBC Chapter 70 (1979) Requirements for Hillside Stabilization

Hillslope (degrees)	Volume of earth moved[a] (yd^3)	Cost of Excavation and Fill[b] (1980 dollars)
0 - 3	0 - 146	0 - 275
3 - 6	147 - 326	276 - 613
6 - 8	327 - 560	614 - 1,054
8 - 11	561 - 874	1,055 - 1,645
11 - 14	875 - 1,308	1,646 - 2,459
14 - 17	1,309 - 1,966	2,460 - 3,697
17 - 19	1,967 - 3,053	3,698 - 5,740
19 - 22	3,054 - 5,422	5,741 - 10,193
22 - 24	5,423 - 11,810	10,194 - 22,203

[a] Assumptions for excavation volume calculations:

1. Natural slope is planar; hillslope is B degrees; maximum permitted slope for finished cuts and fills is θ degrees.
2. Several adjacent lots are cut together as a single development project; cuts are made in a strip parallel to the slope contours.
3. Depth of lot (D) = 90 feet (= 30 yards); Width of lot (W) = 70 feet (= 23 yards).
5. Calculation of volume does not include provision for streets and sidewalks.
6. Volume of earth excavated and placed as fill = V yd^3 per lot is calculated as:

$$V = 1/8\ D^2\ W \sin B\ (\cos B + \cot(\theta - B)).$$

[b] Assumptions for excavation cost:

1. Soil is average for earth excavation; site is a minimum of 5 acres; cuts and fills are balanced; maximum haul distance = 500 feet.
2. Excavation and haul by front-end loader with a two cubic yard capacity at cost of \$1.40 per yd^3; compaction by bulldozer in 12 inch layers over large area at cost of \$0.44 per yd^3 (Pereira, 1980, p. 18-20); therefore, total cost of excavation and compaction is \$1.88 yd^3.

Alternative mitigation rules based on regional earth-science information can be designed to eliminate losses from landslides. Mitigation rules of different comprehensiveness will be associated with different net benefits estimates. Calculation of the benefits and costs can identify the optimum rule, and the optimum level of earth science information, for a successful mitigation program (see equation D-6, p. D-14). Alternative rules utilizing either slope information, or slope and shear strength information together, can be postulated, and estimates of net benefits can be calculated and used to determine the economic consequences of imposing a particular rule. For comparison, the calculations were also made for rules imposed without selection using earth science information: 1) no mitigation; therefore, no benefits (i.e., expected losses continue at present annual rate, and no costs are incurred for mitigation), or 2) mitigation everywhere (maximum gross benefits, maximum mitigation costs).

Two optimum mitigation rules can be identified from among a suite of different programs for which net benefits are estimated, as illustrated by figure D-10. Point A on the figure indicates the net benefits achieved

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Figure D-10. Near here

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by a "mitigation everywhere" strategy (mitigate if average slope is greater than 0.0 degrees or if shear strength is less than 1.0) that assumes there is no information on which to base selective mitigation. If selective mitigation is undertaken according to specified slope thresholds, annualized net benefits reach a maximum at point B, where mitigation would be required in all 100-meter cells having average slopes greater than 8^{o}. If both slope and shear-strength data are available, further refinement of selection can occur, and the maximum net benefits occur at point C, where the slope is greater than 14^{o} or the shear strength is less than 0.49. Point C is the highest point on the surface depicted and represents the strategy that can provide the community with the highest annualized net benefits ($1.7 million).

In formulating the first set of selective rules, the cells in which grading activities according to Chapter 70 of the U.B.C. (International Conference of Building Officials, 1979) would be required are identified solely on the basis of slope information, i.e., the average slope in the cell. Slope rules identify a threshold (minimum) average slope, and require mitigation in cells with slopes steeper than the specified threshold. Under these kinds of rules, the total mitigation costs for the study area decrease as incrementally steeper threshold slopes are used because mitigation is then required in fewer cells. Gross benefits for the study area also decrease as steeper threshold slopes are set and fewer cells require mitigation. For 100-meter grid cells in the study area (which includes a total of 14,255 cells) postulated slope rules require mitigation over a range from 863 cells for average slopes greater than 14^{o} to 13,677 cells for average slopes greater than 2^{o}.

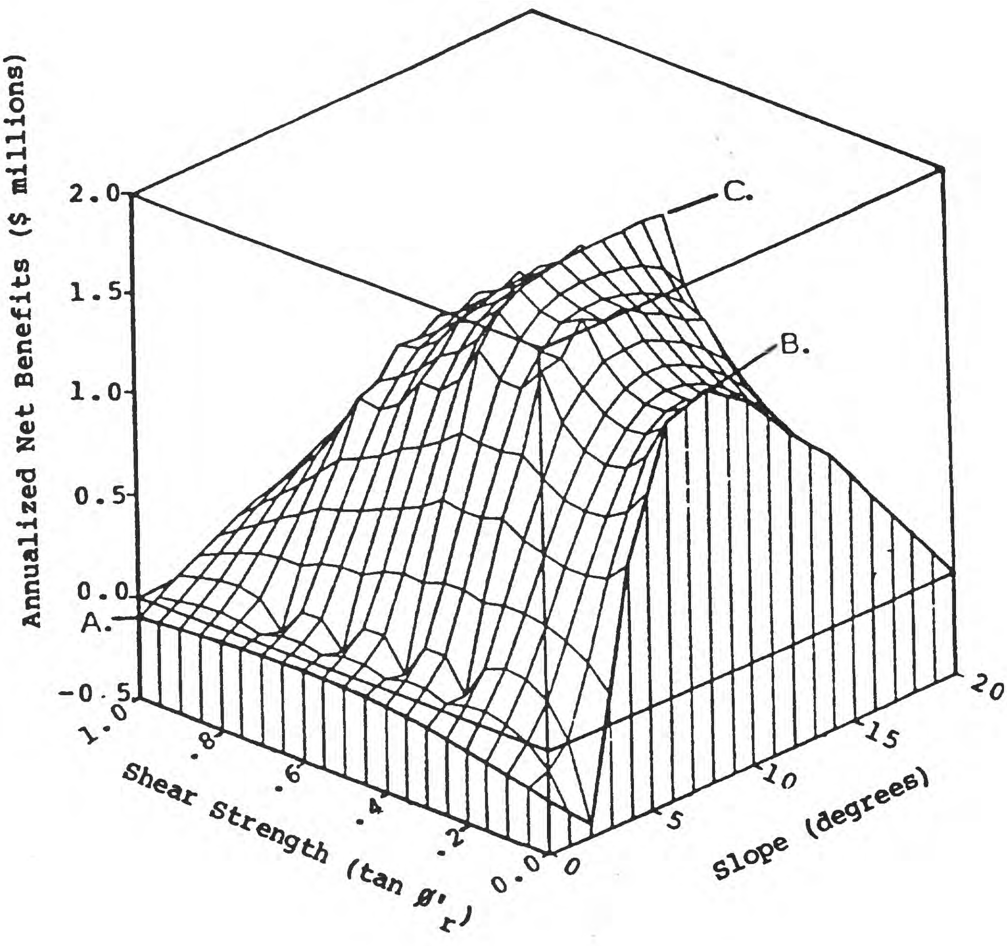

Figure D-10. Net benefits as a function of slope and shear strength thresholds for mitigation

Mitigation under the slope and geology rules is based on threshold values for both average slope and shear strength. If the average slope in a cell is greater than a designated value or if the shear strength is less than a threshold, mitigation is required. Slope and geology rules require mitigation over a range from 1,565 cells for average slopes greater than 14^{o} or shear strength less than 0.30 (out of 14,255 cells) to 13,688 cells with average slopes greater than 2^{o} or shear strength less than 0.30.

Table D-4 shows annual net benefits to the community from the three mitigation rules illustrated by points A, B, and C in figure D-10. The rule

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Table D-4. Near here

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that yields the maximum net benefits to the community is the one requiring mitigation in cells that contain slopes greater than 14^{o} or shear strengths less than 0.49 (fig. D-11). That mitigation strategy produces annualized net

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Figure D-11. Near here

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benefits of $1.7 million, and requires mitigation in 2,569 cells. This compares with net benefits of $1.4 million for the optimum slope rule, where mitigation would be required in the 2,851 cells having an average slope steeper than 8^{o} (fig. D-12), and with negative net benefits of $100,000 for

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Figure D-12. Near here

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requiring the application of U.B.C. Chapter 70 requirements in all of the 14,255 cells in the study area. A decision to use the strategy that produces the maximum net benefits depends on whether the community would be better off by imposing this particular mitigation program over other choices such as a) no mitigation, which would provide no benefits but would require no information and leave any mitigation activity (and cost) to the discretion of the individual property owner, or b) require mitigation everywhere, which would provide maximum gross benefits but would require property owners to undertake costly mitigation activities in many cells where the expected losses from landslides are very low.

Conclusions: the Value of Information

The use of regional physical science information in a statistical format can provide an effective means for evaluating the relative merits of alternative mitigation strategies for a natural hazard such as landslides. By identifying the existing physical state and the mechanical process that governs landslides, it is possible to spatially differentiate the likelihood of a hazardous event among relatively small tracts of land. In addition, it

Table D-4. Annualized Benefits[1] and Costs ($ millions) of Alternative Optimal Mitigation Rules. (Mitigation using only corrective grading according to the cut and fill requirements of International Conference of Building Officials, 1979.)

Rules to Identify Cells where Mitigation is Required	Number of Cells[2] Requiring Mitigation (n)	Annualized Gross Benefits $P(\Delta L)$	Annualized Engineering Cost (K)	Annualized Net Benefits $P(\Delta L)-K$
Mitigate everywhere	14,255	4.9	5.0	- 0.1
Average slope steeper than 8° (A rule)	2,851	3.1	1.7	1.4
Average slope steeper than 14° or shear strength less than 0.49 (B rule)	2,569	3.1	1.4	1.7

1 Using a real discount rate of 10 percent annually.

2 100-meter cells.

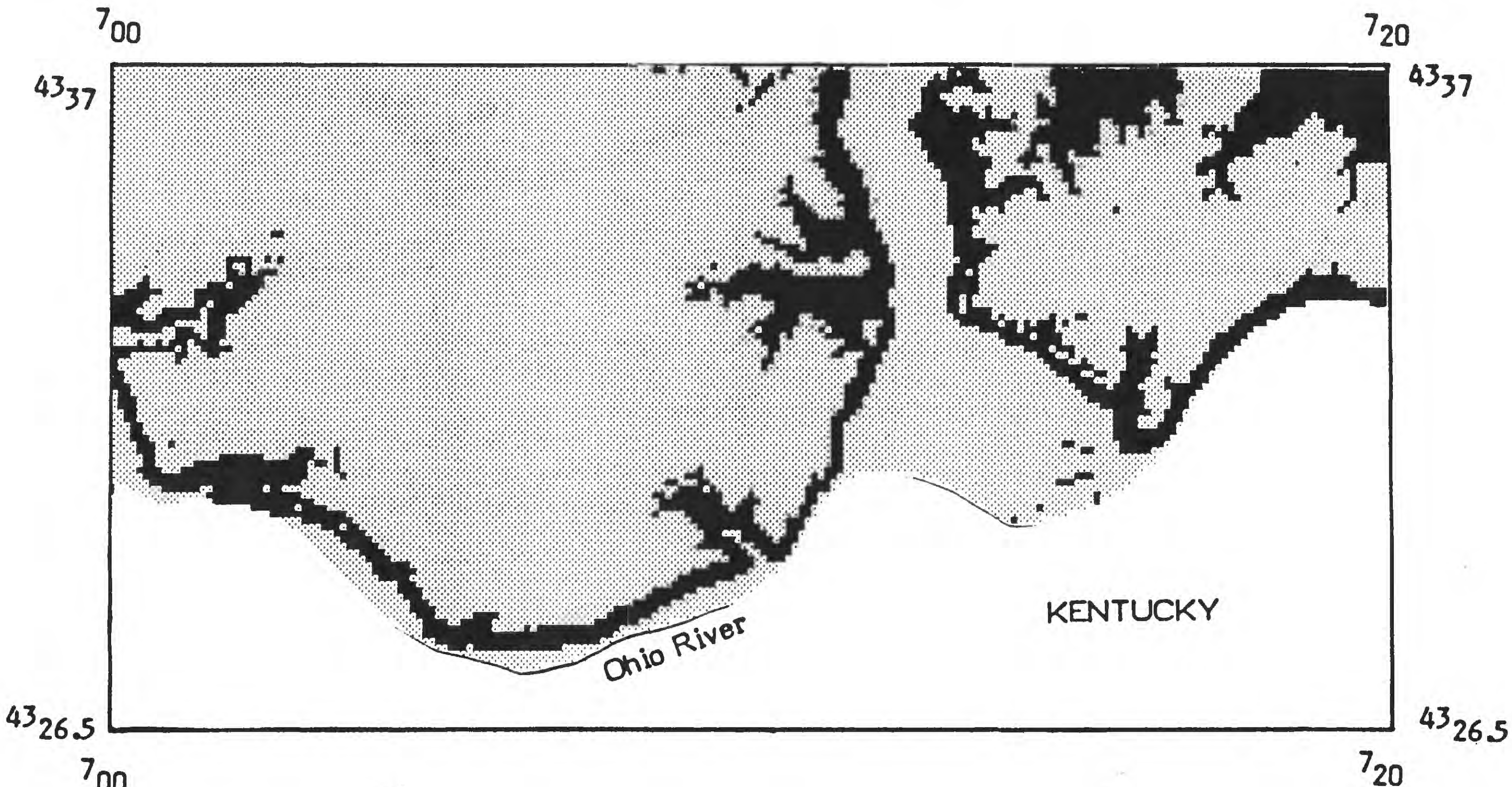

Figure D-11. CELLS THAT WOULD REQUIRE MITIGATION UNDER OPTIMUM RULE USING SLOPE AND GEOLOGY (Shown in black) (100-meter cells; UTM coordinates)

The optimum slope-and-geology rule identifies those cells where slope exceeds 14° or where shear strength equals or is less than 0.49.

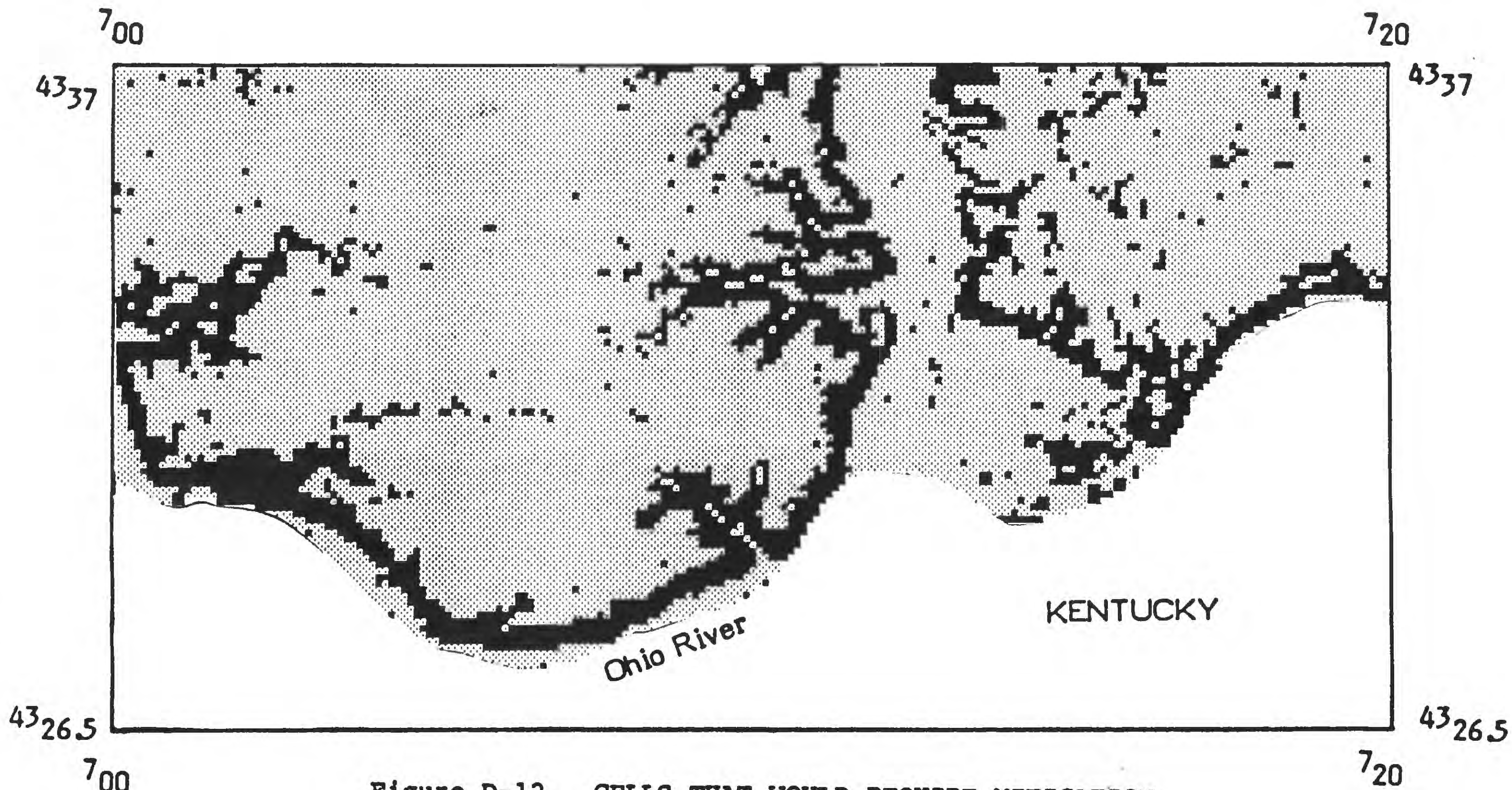

Figure D-12. CELLS THAT WOULD REQUIRE MITIGATION UNDER OPTIMUM RULE USING SLOPE ONLY (Shown in black) (100-meter cells; UTM coordinates)

The optimum slope-alone rule identifies those cells where slope exceeds 8°.

is possible to assess the extent to which property is at risk and to estimate the expected property value loss that can be avoided if mitigation is undertaken.

Results from the Cincinnati, Ohio, study area show that mitigation strategies that are spatially selective are more efficient than strategies that do not discriminate among areas having different levels of hazard. The optimum strategy is identified as that requiring mitigation in cells with average slopes greater than 14^{o} or shear strength less than 0.49, which achieves a maximum of $1.7 million in estimated annualized net benefits. Comparing that maximum of $1.7 million to the $1.4 million in estimated annualized net benefits identified as the maximum to be achieved under strategies based solely on slope information (cells with average slopes greater than 8^{o}) indicates that $300,000 annualized marginal net benefits would be derived from having and using regional geologic information to assist in selecting the cells in which the community requires mitigation (Table D-4). This marginal improvement in benefits is achieved for a one-time cost of approximately $20,000 for compiling surficial geologic data for the study area.

The procedures developed during this study utilize regional data to effectively discriminate the different levels of landslide hazard in different tracts of land in a major U.S. metropolitan area. Because the regional information describes a state of nature, the methodology could also be used in assessing the likelihood of future disasters and to identify where post-event disaster relief is most likely to be requested. In addition to the capability to estimate the benefits and costs of different mitigation strategies, the techniques developed in this study also provide a measure of the value of the regional earth-sciences information utilized in obtaining the benefits of mitigation. By comparing the net benefits of mitigation rules based on different types of information (e.g., slope only vs. slope and shear strength) the marginal benefits of acquiring geologic information can be estimated and compared with estimates of the cost of acquisition. Figure D-13 illustrates how different areas are affected by the different optimum mitigation rules.

Figure D-13. Near here

The application of the specific mitigation rules postulated for this study to Cincinnati, Ohio, neighborhoods, would be premature without further research, particularly with regard to several of the limiting assumptions. Research to match specific engineering solutions to specific hillside conditions might define equally effective, lower-cost alternatives to cut-and-fill specifications that should be used in estimating costs of mitigation. Further research to delineate the regional distributions of ground-water conditions could improve estimation of the probability of a landslide event. The assumption that there is 100-percent destruction in a cell 100 meters on a side reflects the crudeness of the data available. For a mitigation program to be implemented on a house-to-house basis, which might reduce the 100-

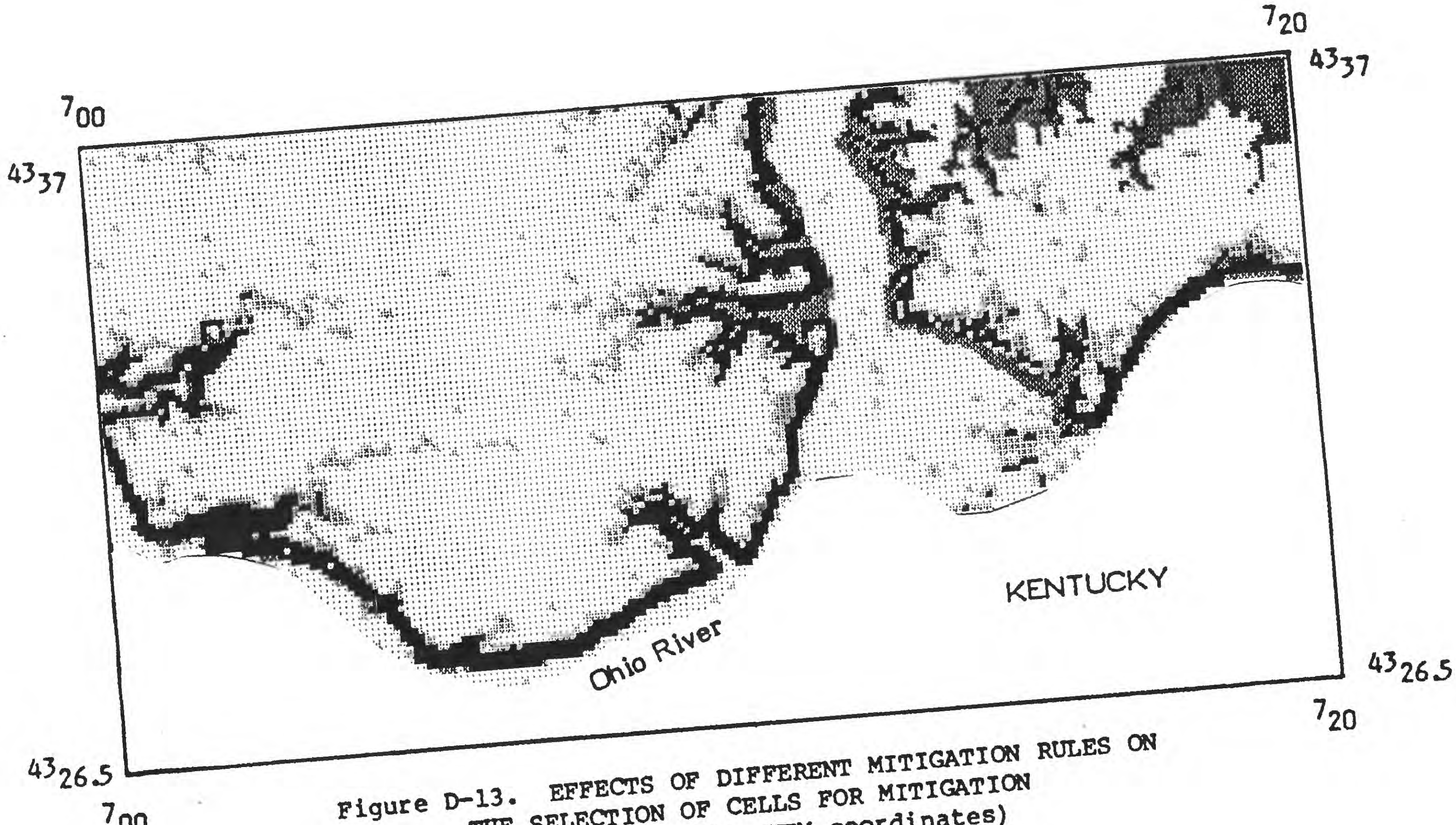

Figure D-13. EFFECTS OF DIFFERENT MITIGATION RULES ON THE SELECTION OF CELLS FOR MITIGATION (100-meter cells; UTM coordinates)

Explanation

Mitigation required under optimum rule for slope and geology, <u>and</u> under optimum rule for slope alone

Mitigation required under optimum rule for slope alone, <u>but not</u> under optimum rule for slope and geology

Mitigation required under optimum rule for slope and geology, <u>but not</u> under optimum rule for slope alone

Mitigation not required under optimum rule for slope and geology, <u>nor</u> under optimum rule for slope alone percent destruction in a 100-meter cell to as little as 10 percent, a further refinement of the data collected at the local community level would be required. With such additional detail, these approaches might be applied directly to city planning. The marginal net benefits of acquiring additional detail could be estimated, and an optimum level of detail identified as that providing the maximum net benefits. It is important to note, that the regional data are most appropriate for planning, and that conclusions regarding the stability and most effective kind of mitigation activity for a specific site will continue to require site examination and sound engineering judgement in design and construction of structures.

The techniques developed in this study provide an economic basis for community decisions regarding engineering design and construction requirements for landslide-hazard mitigation. They can also be used to provide individual investors/developers with a procedure by which a preliminary measure of expected value can be estimated. Although the study area is small, it appears to be representative of the landslide processes, states of nature, and triggering causes for landslides in large parts of the Appalachian Plateau. For applications in other geomorphic regions, extensive modification of the probability equation will be required.

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